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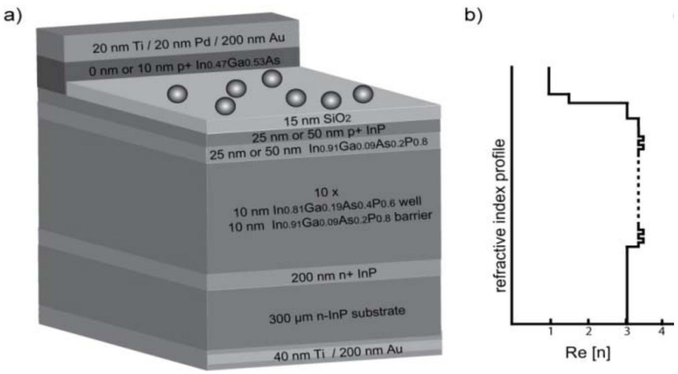

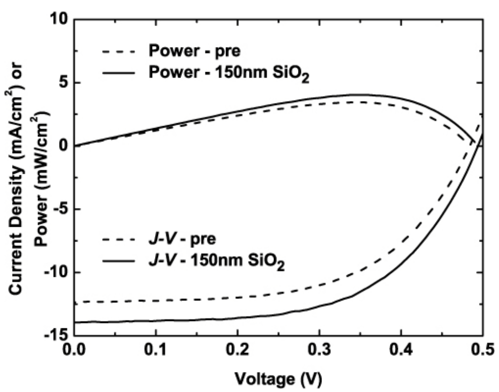

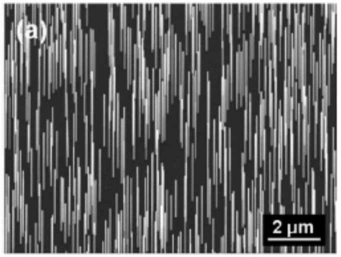

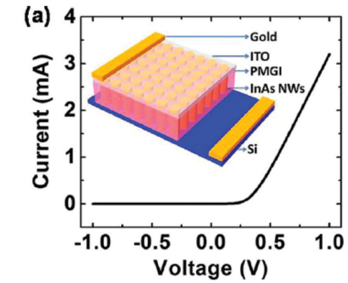

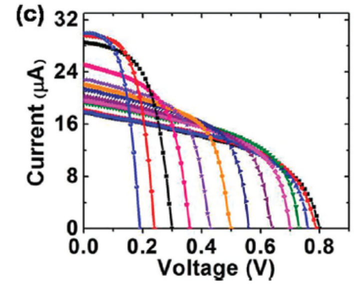

High-efficiency photovoltaics based on semiconductor nanostructures

Program Team: PV

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University of Texas at Austin/University of California at San Diego

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26 May 2010

DE-FG36-08GO18016

Overview

Timeline

- Start date: 1 February 2008
- End date: 31 January 2011
- Percent complete: 70%

Budget

- Total project funding
  - DOE share: $604,000
  - Contractor share: 20% cost sharing
- Funding received in FY09: $224,000
- Funding for FY10: $140,000 to date

Barriers

- Very high-efficiency solar cells an essential component for concentrating PV
- Robustness under spectral variability desirable
  - ⇒ single pn junction structures
  - ⇒ multijunction, non-series connected devices

Partners

- Project lead:
  University of California, San Diego
  University of Texas at Austin
- Interactions/collaborations:
  Spire Semiconductor
  Jet Propulsion Laboratory
  Boeing/Spectrolab

Challenges, Barriers or Problems

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Challenges

- High-efficiency solar cells required for applications such as terrestrial concentrating photovoltaics
- Quantum-well solar cells and related structures offer potential for very high efficiency (~45% to >60% theoretically predicted efficiencies)
- Substantial challenges in materials and devices:
  - High quality heterostructures to minimize recombination rates
  - Engineering carrier and photon transport paths to achieve simultaneously high efficiency in photon absorption and photogenerated carrier collection

Importance

- Multijunction tandem solar cells can provide high efficiency, but potentially sensitive to terrestrial spectral variations
- Single pn junction structures (e.g., quantum-well, intermediate-band solar cells, etc.) can theoretically provide comparable efficiency with much less spectrum sensitivity
- Success in developing high-efficiency devices of these types should improve viability of large-scale concentrating photovoltaic systems

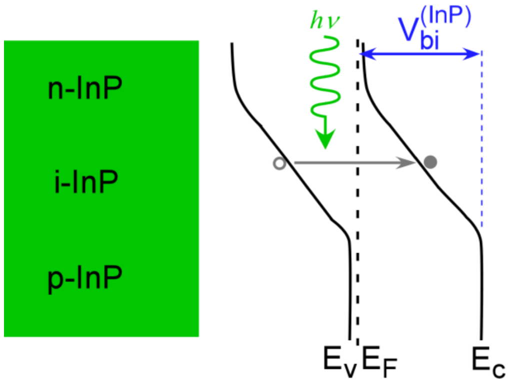
Objectives

- Overall objective: development and demonstration of high-efficiency photovoltaic device concepts based on semiconductor nanostructures
  - Quantum-well solar cells and related devices
  - Nanowire-based solar cells
- 2009-2010 objective: build upon initial demonstrations of key device concepts to explore routes to increased power conversion efficiency
  - Engineering of waveguiding properties of quantum-well solar cell devices for photon management
  - Optimization of internal quantum-well structure for increased optical absorption
  - Improved growth and fabrication of nanowire-based solar cell structures

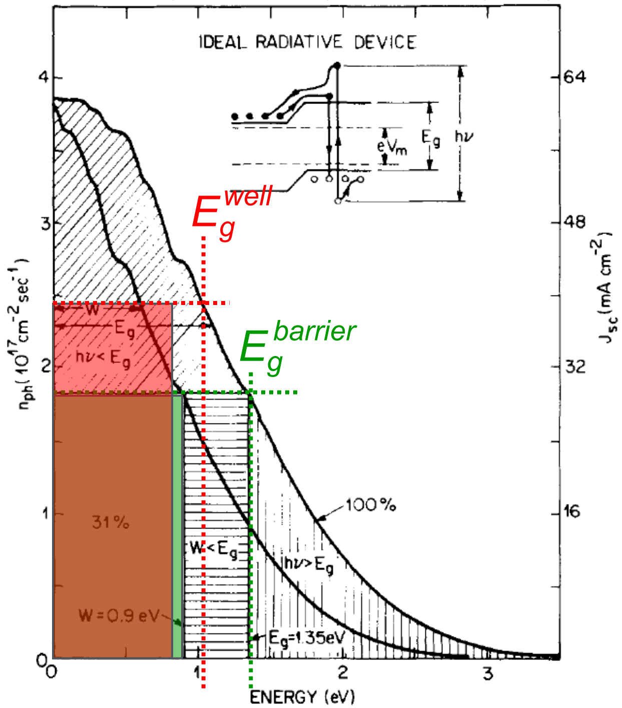
Relevance

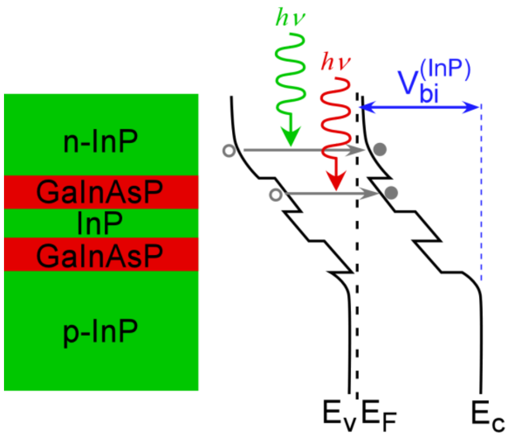
- 2009-10 objectives represent key steps in realization of devices with high absolute levels of power conversion efficiency
- High absolute power conversion efficiency in quantum-well solar cells or other single-pn junction photovoltaic devices will enable high efficiency to be achieved over broad range of illumination spectra
- Devices developed in this project could be a key component in terrestrial concentrating photovoltaic systems

Approach – quantum-well solar cells



[C.H. Henry, *J. Appl. Phys.* **51**, 4494 (1980).]





[cf. K. Barnham, G. Duggan, *J. Appl. Phys.* **67**, 3490 (1990).]

Predicted maximum power conversion efficiencies for quantum-well solar cells are ~45% to ~63% (vs. ~31% to ~37% for "conventional" solar cell)

[G. Wei, K.T. Shiu, N.C. Giebink, S.R. Forrest, *Appl. Phys. Lett.* **91**, 223507 (2007); S.P. Bremner, R. Corkish, C.B. Honsberg, *IEEE Trans. Electron Devices* **46**, 1932 (1999).]

Quantum well solar cell challenges

- Multiple-quantum-well materials issues, e.g., critical thickness, interface quality, recombination
- High quantum efficiency in long-wavelength absorption
- Efficient carrier extraction from quantum wells

Approach – quantum-well solar cells and photon management

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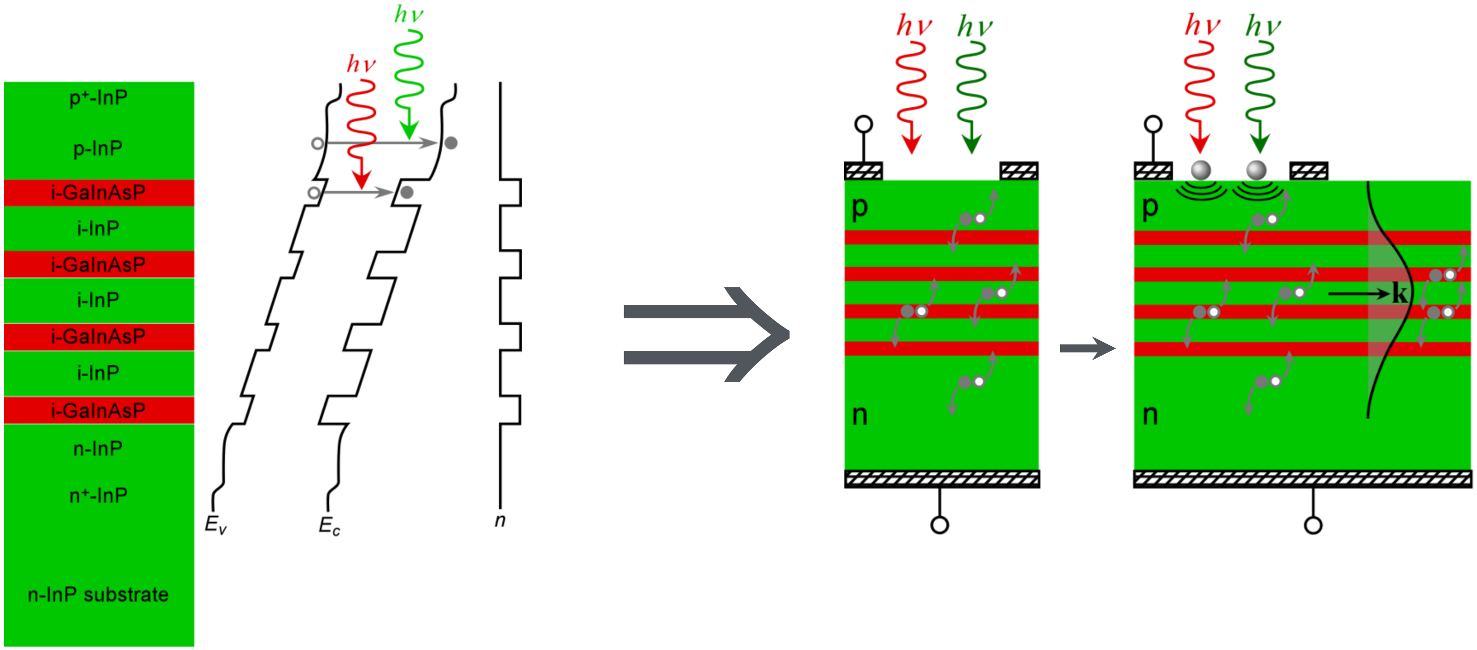
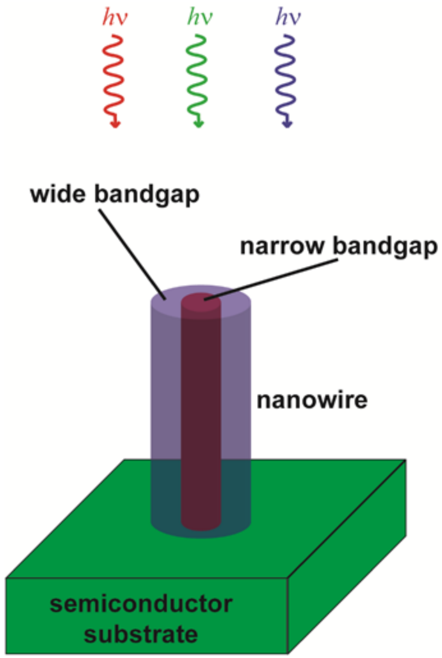
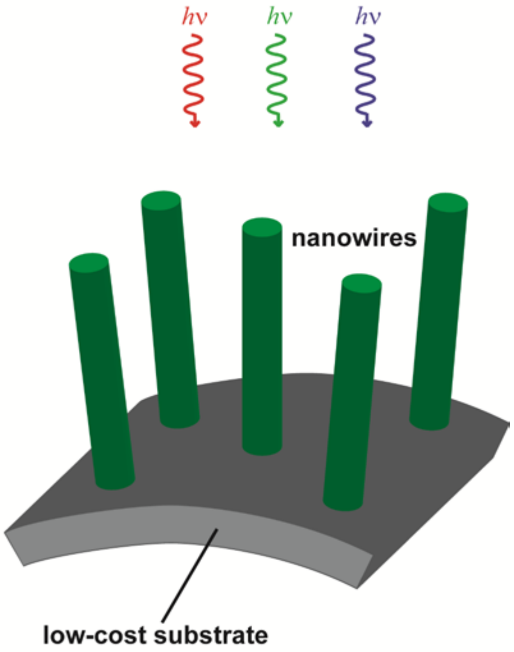


- In conventional device geometry, design requirements for efficient photon absorption and efficient photogenerated carrier collection are incompatible
  - Efficient absorption requires thickness ~1um
  - Efficient carrier collection requires thickness ~0.2-0.3um
- Index contrast leads to optical confinement in multiple-quantum-well region
  - ⇒ optically confined, lateral photon propagation paths supported
- Metal (or dielectric) nanoparticles can scatter photons into lateral paths
  - Broader-band effect than, e.g., grating scatterers
  - Easy to fabricate

Approach – nanowire geometries





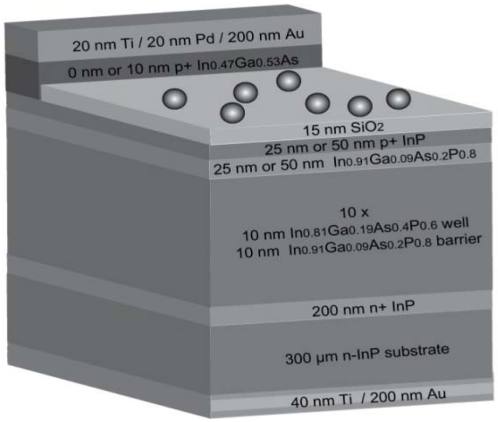
- Core-shell nanowires can enable realization of quantum-well solar cell concept in alternate geometry with potentially relaxed lattice mismatch constraints
- Nanowire-based photovoltaics could facilitate use of high-quality, crystalline semiconductor material with support substrates that are low-cost, flexible, etc.

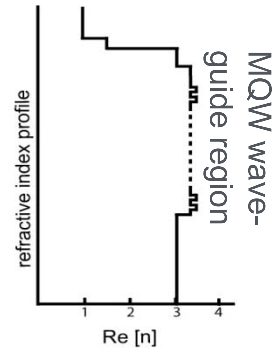
Collaborations

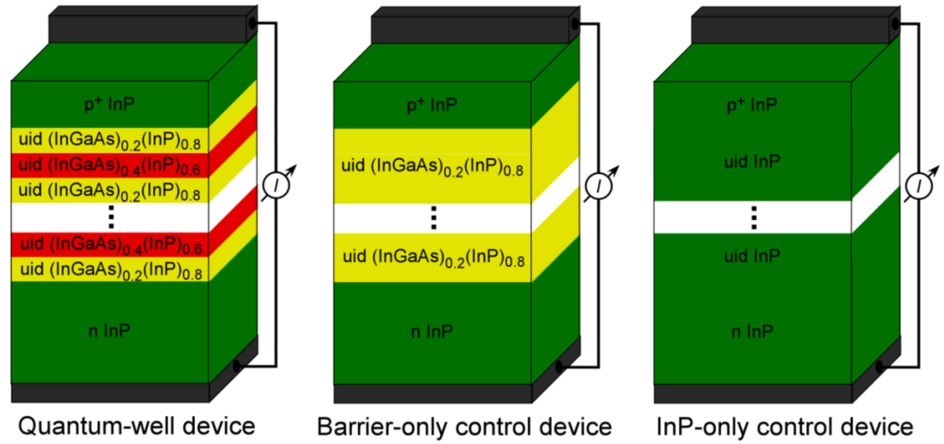
- Key project collaborators
  - Spire Semiconductor: collaboration in development and supply of epitaxial heterostructure material for quantum-well solar cells and related structures.
  - NASA Jet Propulsion Laboratory: collaboration in development and implementation of wafer thinning and substrate removal processes.
  - Boeing/Spectrolab: collaboration in adaptation of nanoparticle scattering effects for multijunction tandem solar cells.
  - University of Karlsruhe: collaboration in development of quantum dot and dot-in-well structures for high-efficiency solar cells.

- Collaborators listed here are not funded through this DOE program.

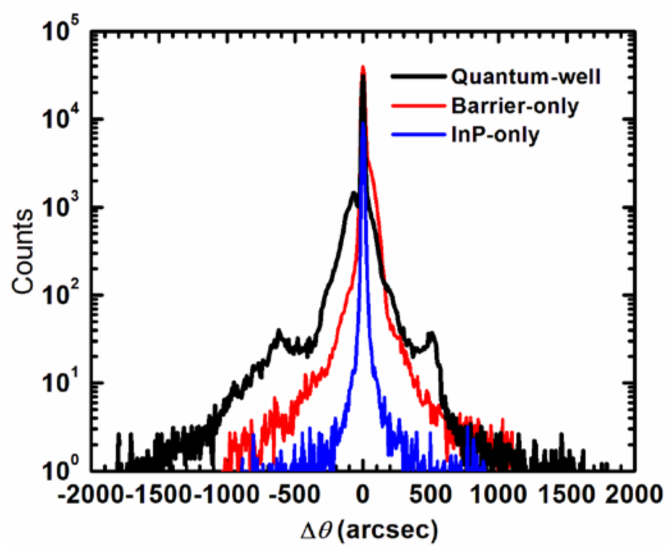
Results – QWSC demonstration

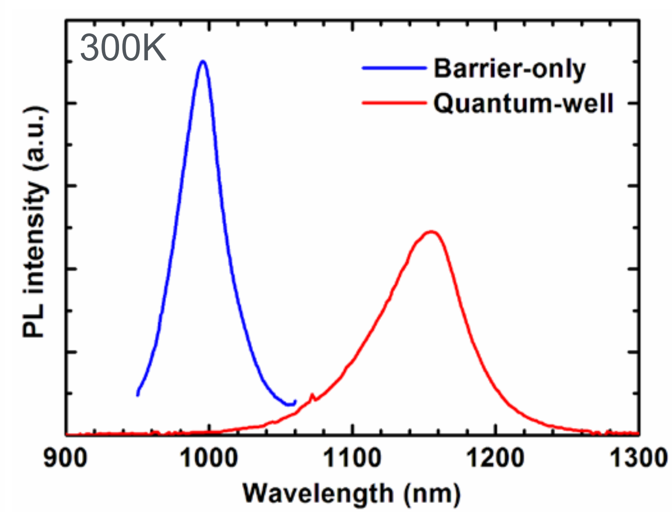




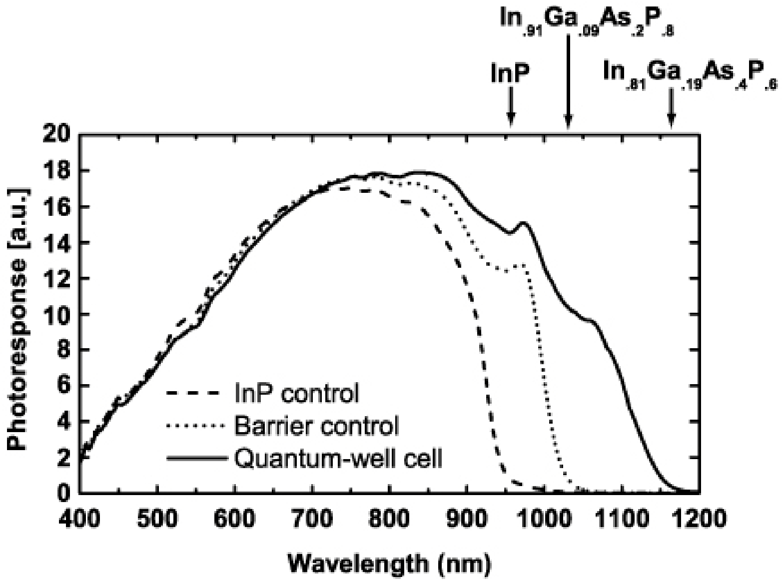


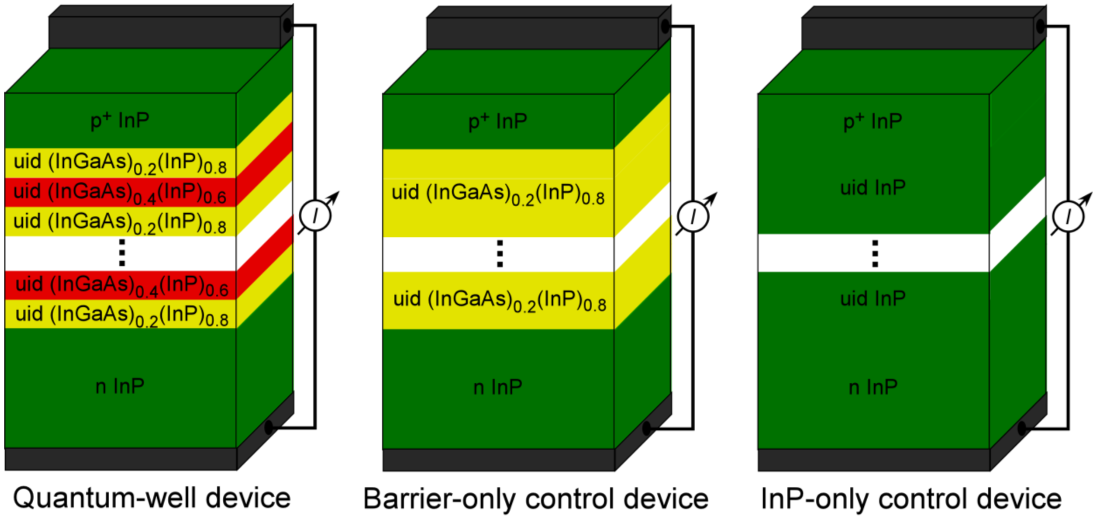
- MQW absorption and nanoparticle scattering concepts demonstrated in lattice-matched InP/InGaAsP MQW structures grown by MOCVD
- Room-temperature photoluminescence and x-ray diffraction confirm reasonable lattice match, reduced band gap in quantum-well layers

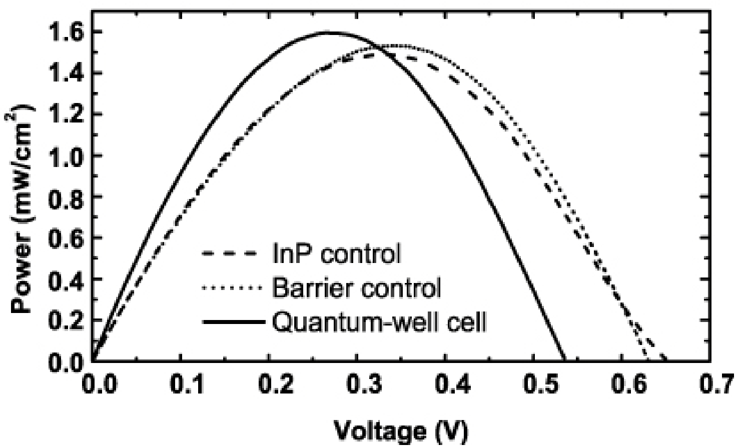




Results – QWSC demonstration

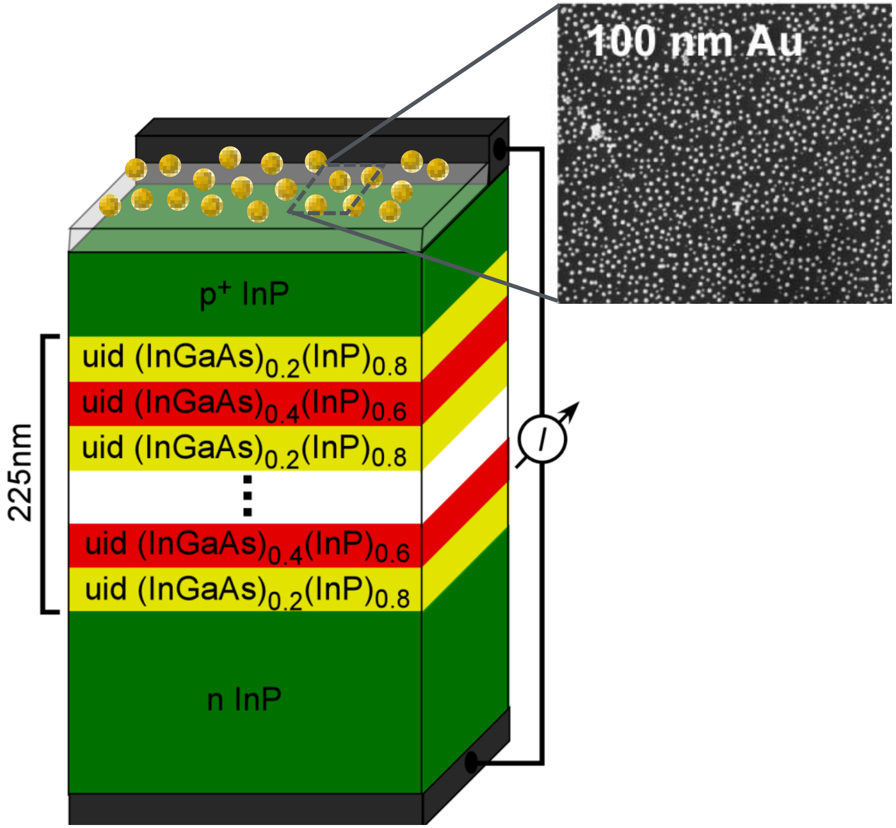


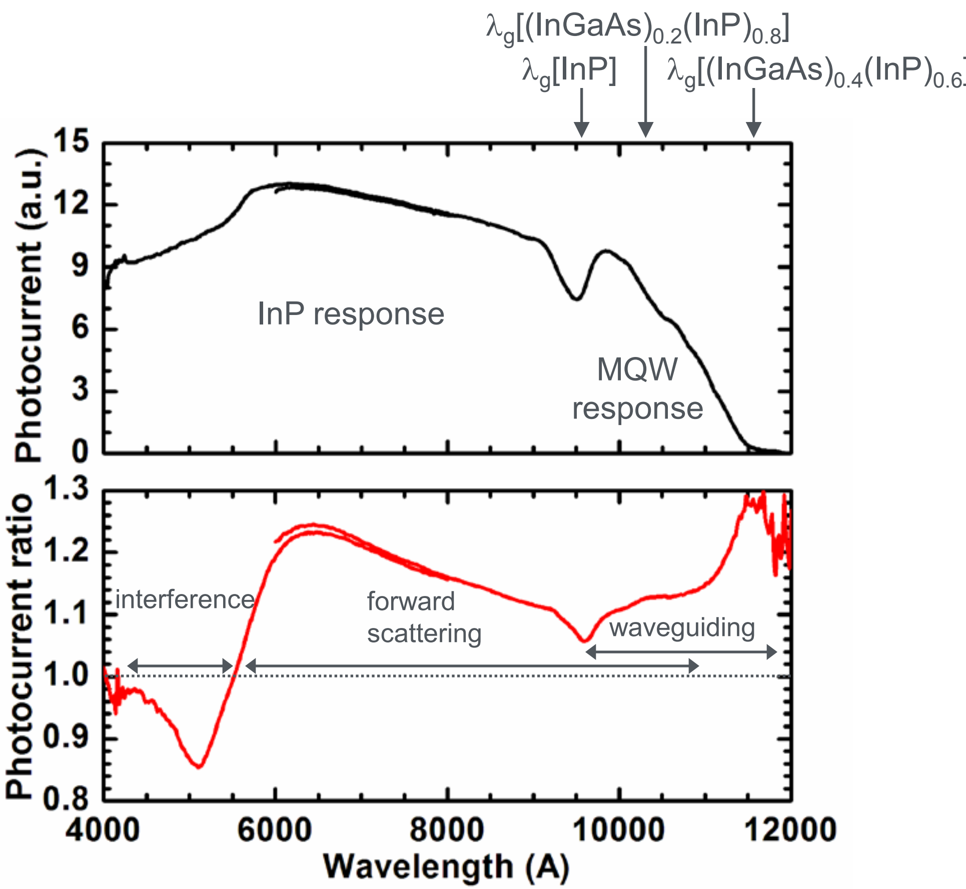




- Barrier-only and quantum-well devices show clear photocurrent response at wavelengths beyond InP band gap
- Quantum-well device shows ~5-7% increased power output over barrier-only and InP-only control devices

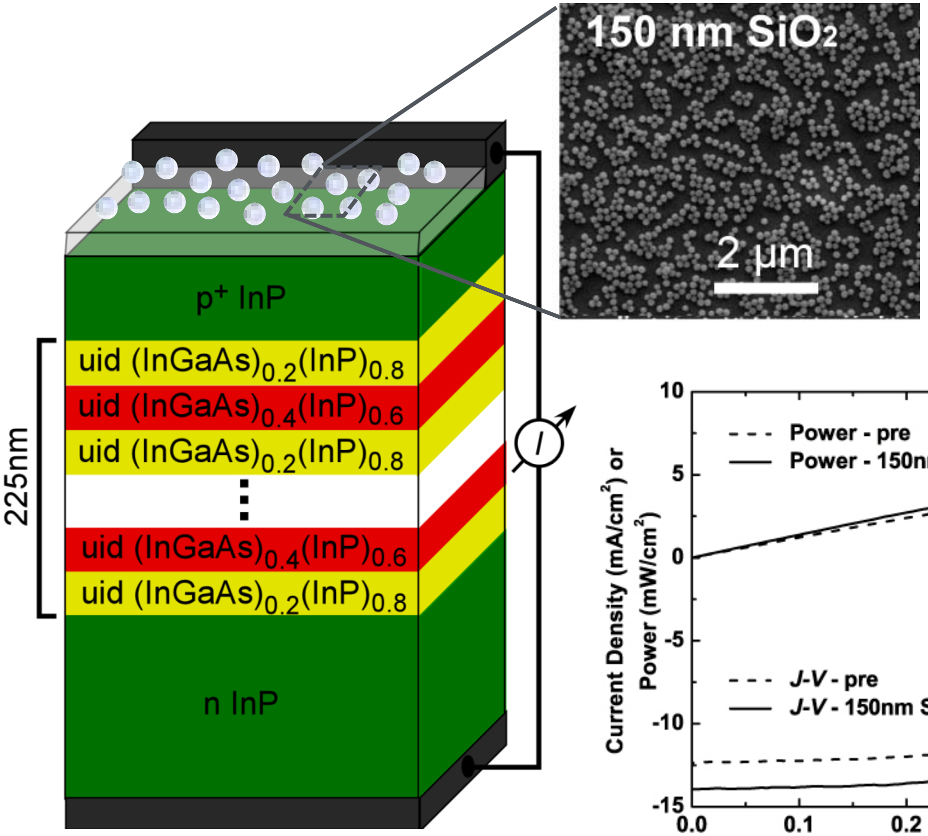
Results – QWSC demonstration

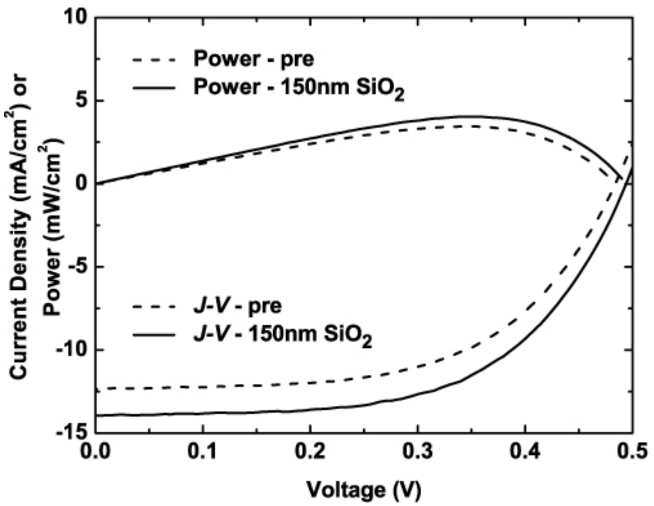


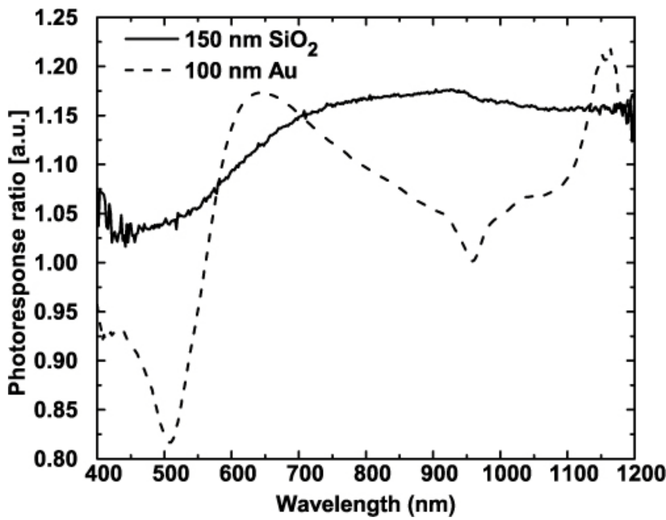


- InGaAsP-InP multiple-quantum-well solar cell exhibits clear response below InP bandgap due to MQW absorption
- Functionalization with 100nm Au nanoparticles generates plasmonic effects:
  - Forward scattering into semiconductor device region
  - Excitation of optically confined modes in MQW region

Results – QWSC demonstration

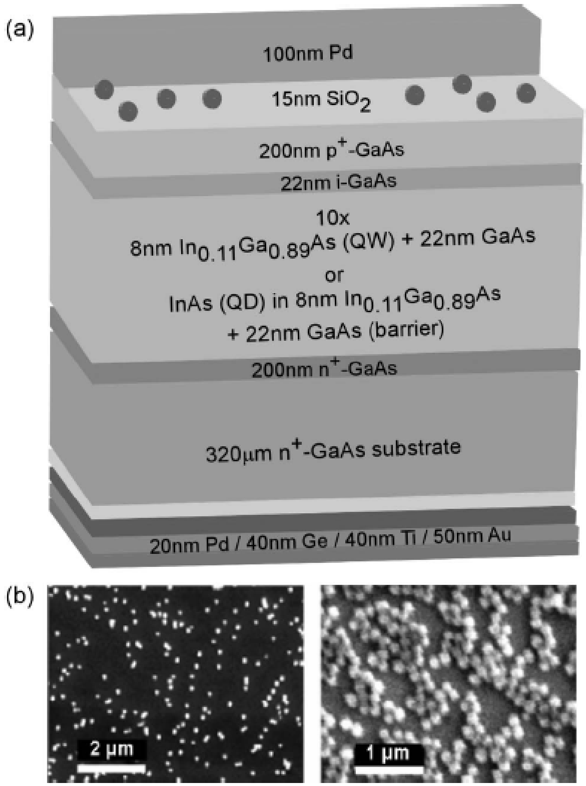


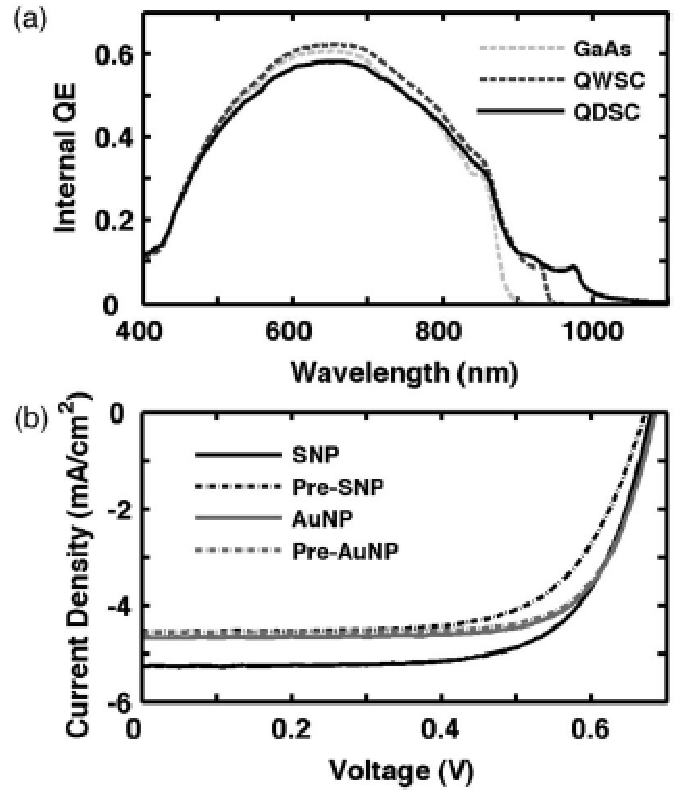




- Highly unoptimized device shows ~13% increase in short-circuit current density, ~17% increase in power conversion efficiency due to SiO_2 nanoparticle scattering
- Au nanoparticles yielded ~7% increase in current, ~1% increase in power conversion efficiency

Results – Quantum-dot solar cells





- InAs/InGaAs/GaAs quantum dot-in-well solar cell structures also successfully fabricated and demonstrated
- Quantum-dot structures enable photocurrent response to be extended to longer wavelengths than quantum-well structures
- Nanoparticle scattering effects also enable improved absorption efficiency

Results – engineered quantum-well structures

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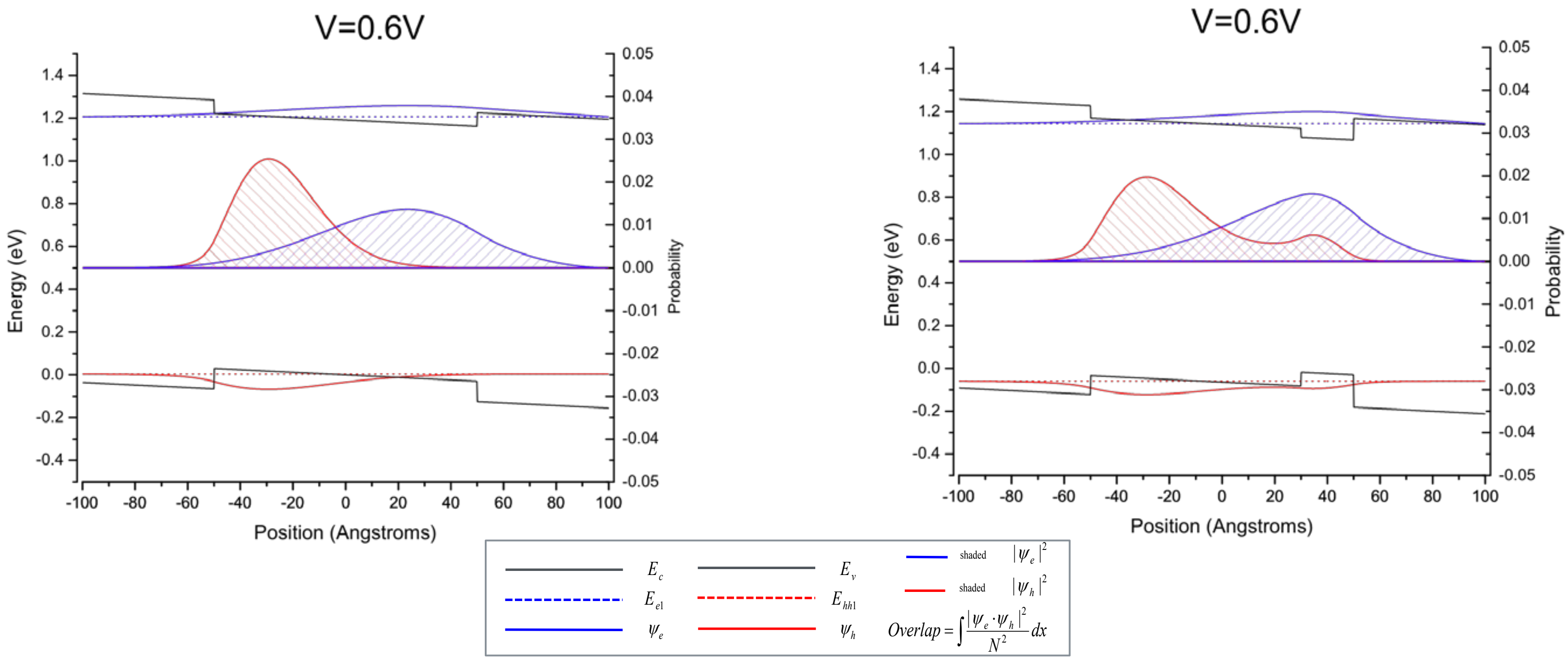
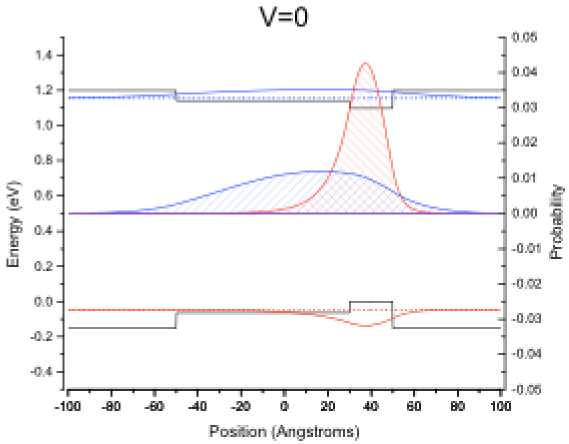
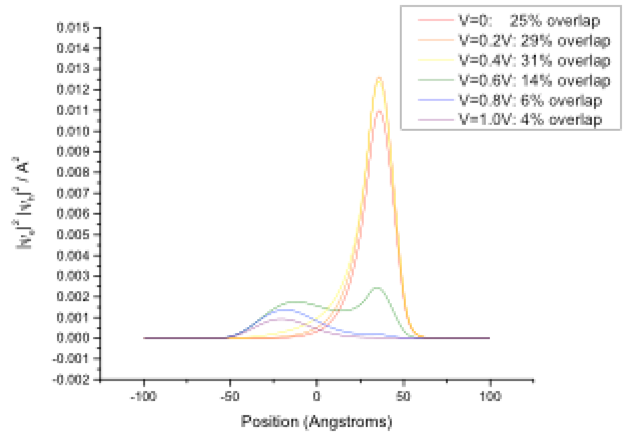
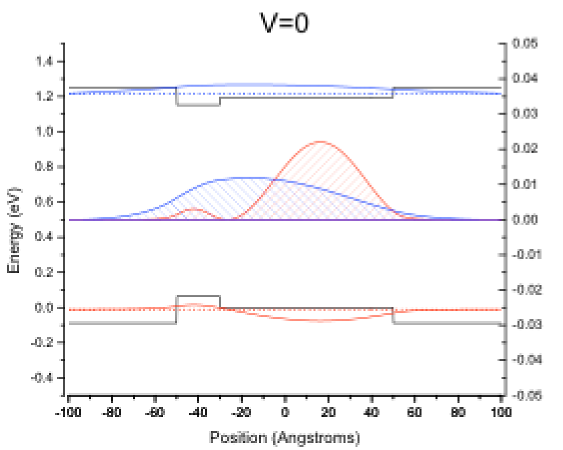


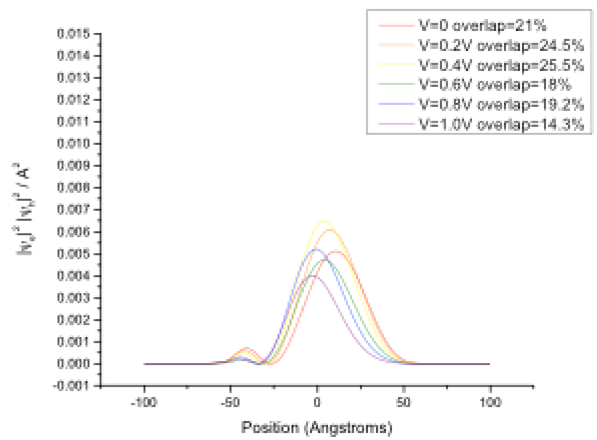
- Introduction of internal structure within quantum well can substantially alter electron-hole wavefunction overlap and optical absorption efficiency
- 1D Poisson-Schrodinger simulations allow internal structure and resulting wavefunctions in quantum wells to be computed and optimized

Results – engineered quantum-well structures









- Bias dependence of electron and hole wavefunctions must be taken into account in device designs
- Samples have been grown by MOCVD and experimental measurements are underway

Results – photon propagation analysis

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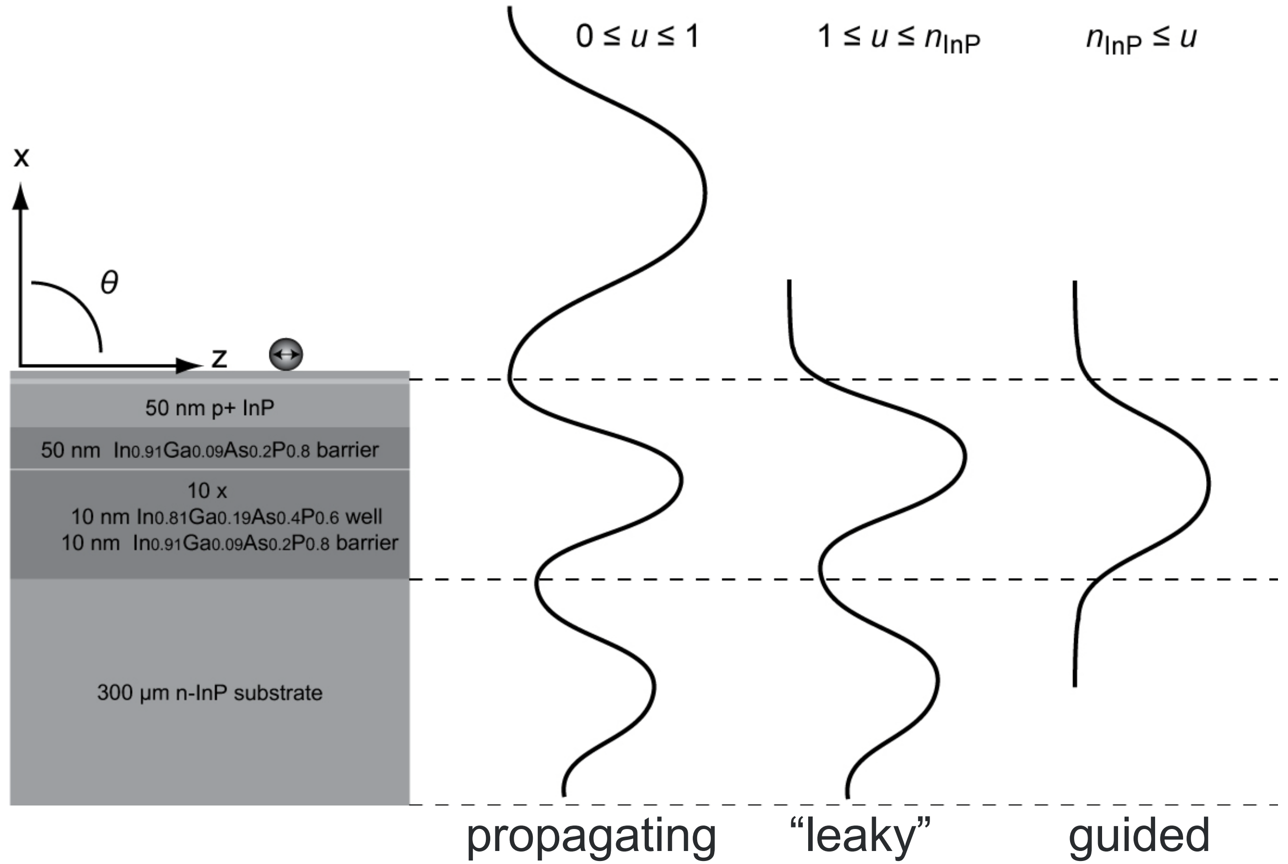
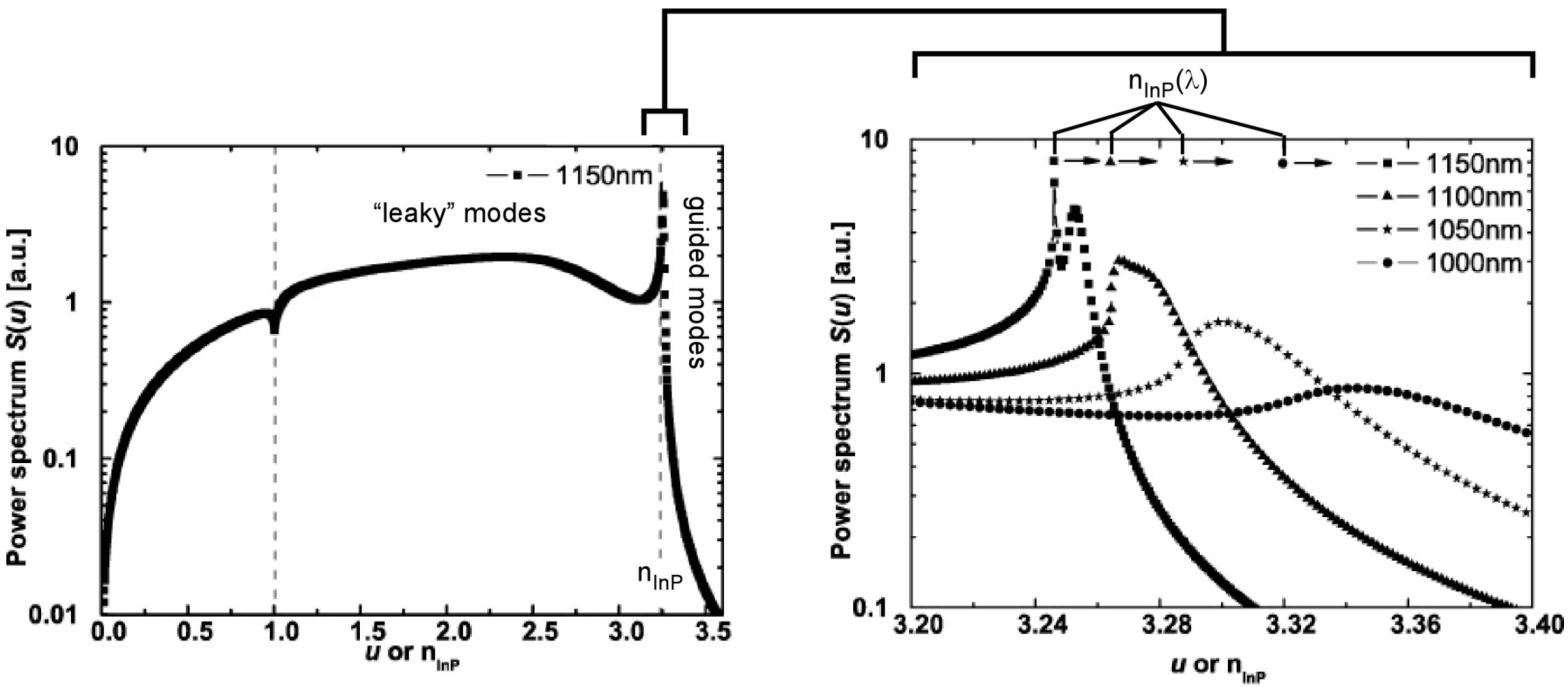


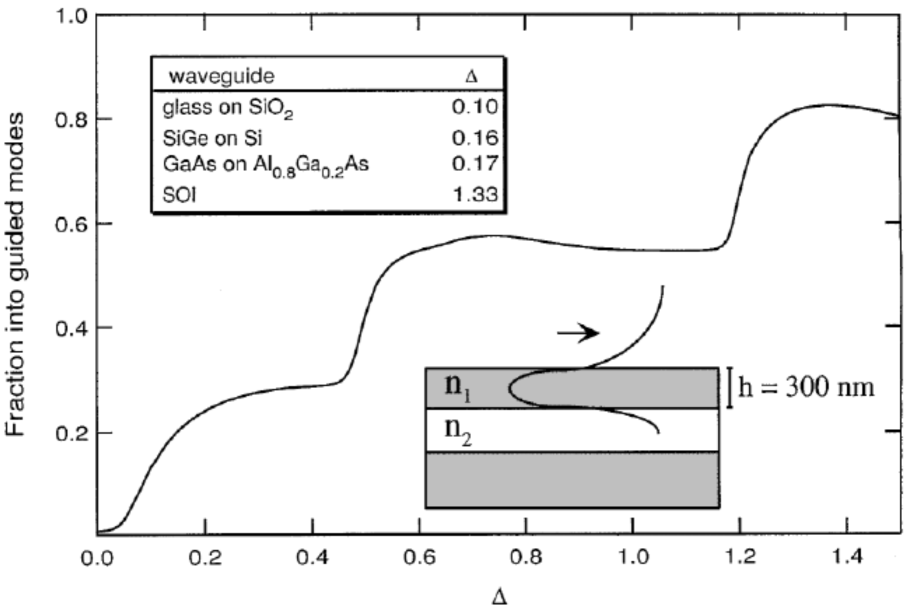
- Coupling of photons scattered by nanoparticles into waveguide modes modeled using horizontal radiating dipole at device surface
- "Leaky" and guided modes could contribute to additional absorption and photocurrent generation in semiconductor

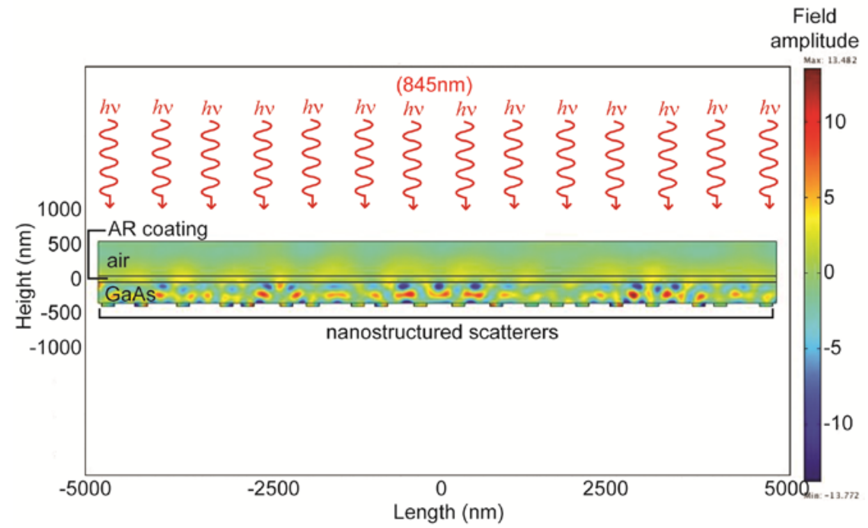
Results – photon propagation analysis



- Coupling efficiency into guided modes <10%, but coupling into "leaky" + guided modes ~80-90%
- Key issue for efficient coupling into guided modes is large refractive index contrast

Results – optimized device design

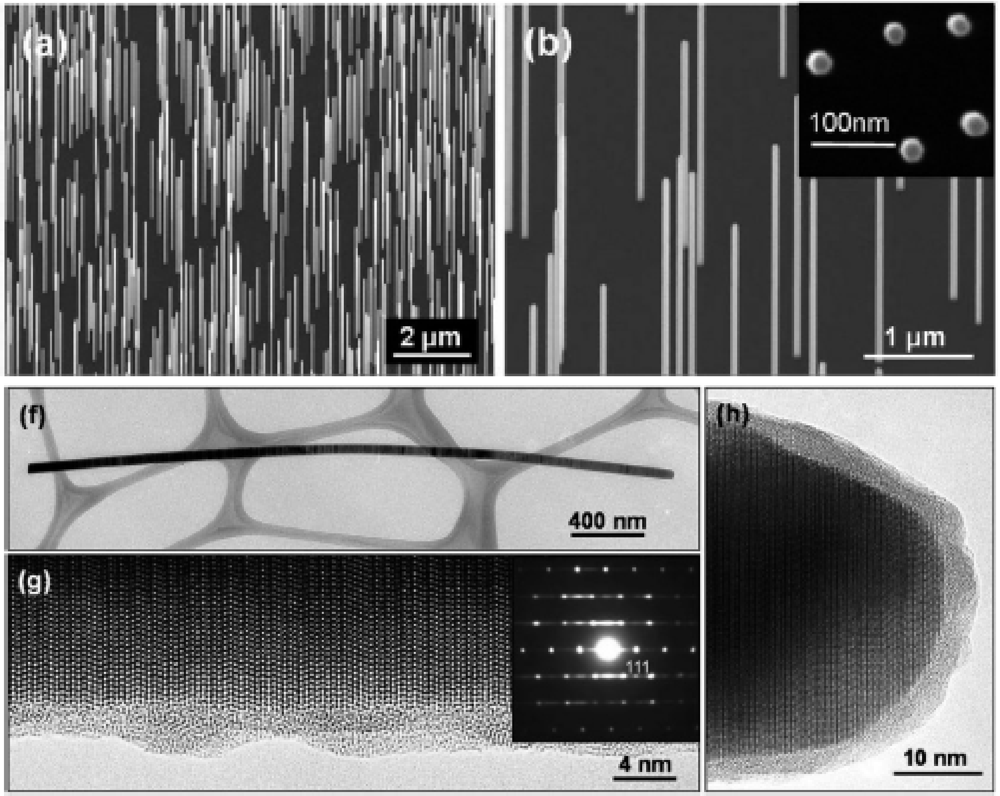


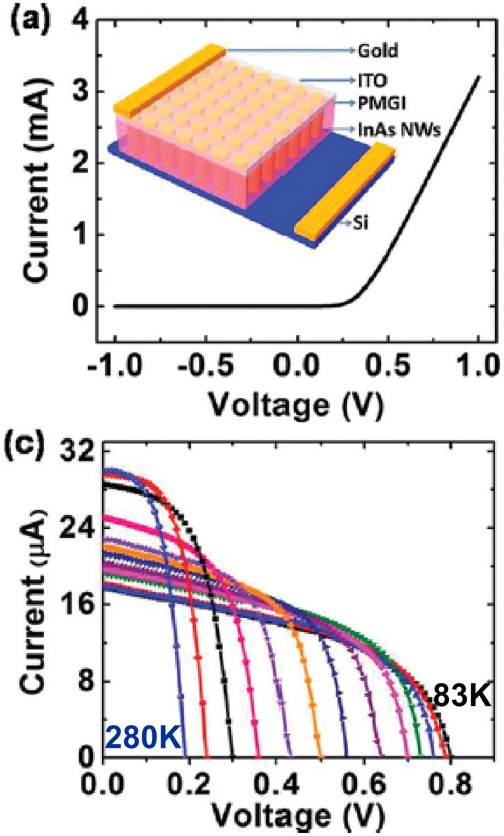


[B. J. Soller, H. R. Stuart, D. G. Hall, *Opt. Lett.* **26**, 1421 (2001).]

- High refractive index contrast allows ~60-90% coupling efficiency of scattered light into guided modes over broad range of wavelength
- Wafer thinning/bonding and related materials integration techniques enable quantum-well solar cell structures with optimum waveguiding and coupling
- Preliminary simulations indicate that with minimal optimization, >1.25x improvement in efficiency compared to same cell without scattering (but with antireflection coating) is attainable

Results – nanowire growth and devices





- n-InAs nanowires successfully grown on Si (111) substrates
- InAs nanowires on Si exhibit photovoltaic device behavior, but with low power conversion efficiency (~1-2.5%)
- InAs nanowires can eventually serve as core of high-efficiency core-shell nanowire heterostructure photovoltaic device

Results – nanowire heterostructure growth

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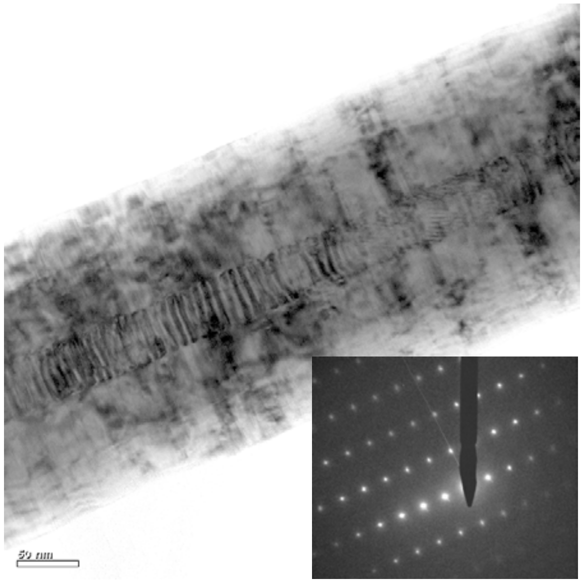
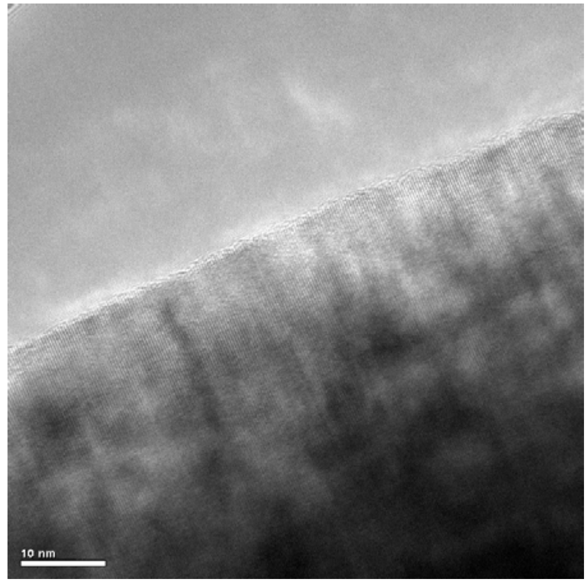
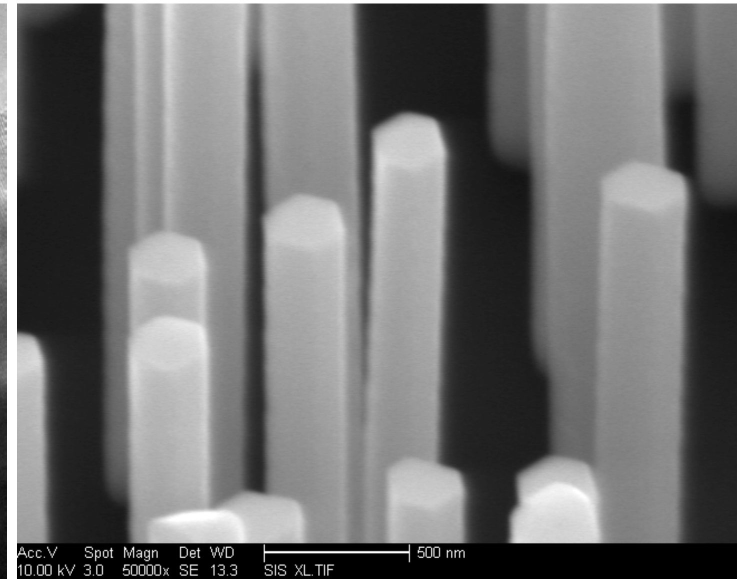
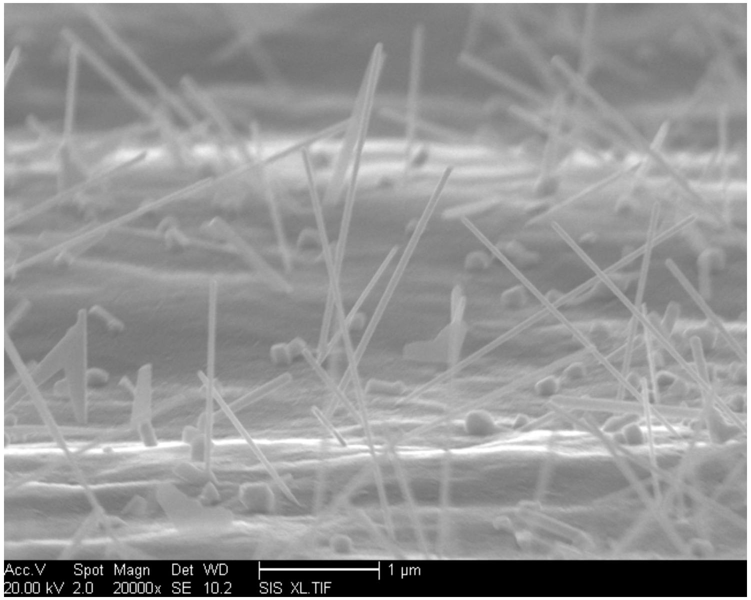


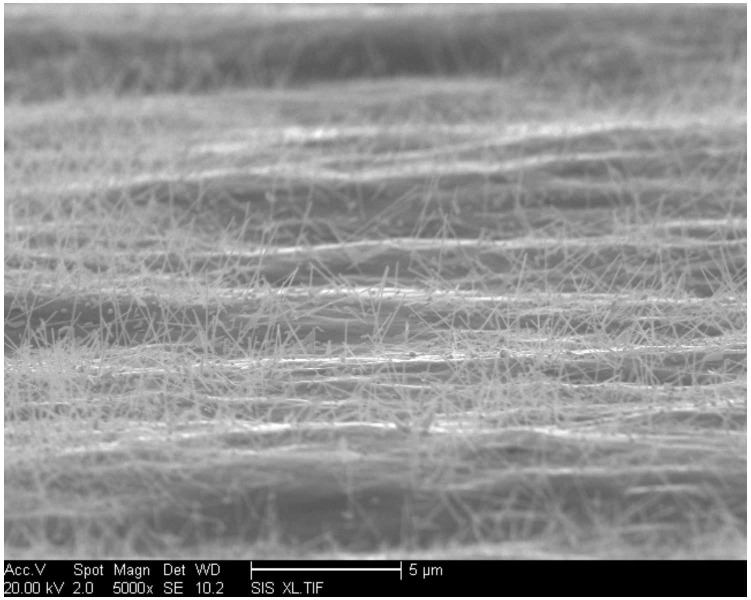




- Growth of uniform core/multi-shell heterostructures (InAs/InGaAs/GaAs/InGaP) successfully demonstrated
- Core/multi-shell heterostructures could serve as basic element of high-efficiency nanowire photovoltaic devices
- Interestingly, nanowires are (111) zincblende rather than wurtzite, as is typical

Results – nanowire growth on low-cost metal foil substrate





InAs nanowires grown on Al foil

- InAs nanowires have been successfully grown by MOCVD directly on low-cost metal foil substrates, e.g., Au or Cu foils
- High-quality nanowire growth on low-cost substrates could help enable low-cost, high-efficiency nanowire-based photovoltaic devices

Budget Status and Potential for Expansion

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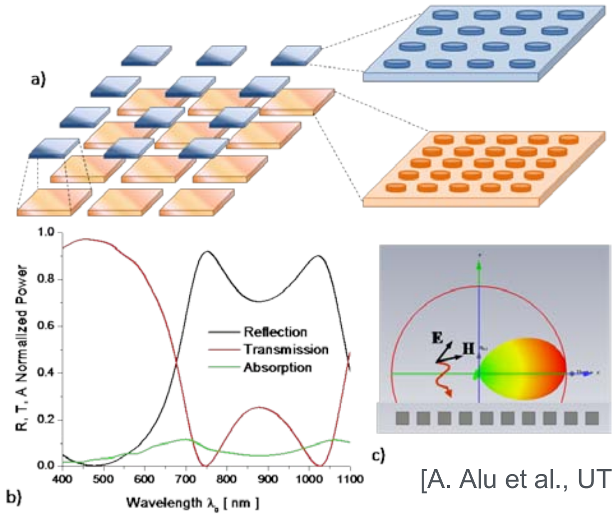
- Project is on budget
  - Total DOE funding of $604,000 to date + 20% cost share
  - In process of transitioning portion of funding from UCSD to UT Austin
- Potential area for expansion: integration of nanostructure scattering and photon management concepts into optical slab concentrator structures for new high-efficiency photovoltaic device concept:



[A. Alu et al., UT Austin]

- Optical metamaterials enable wavelength-dependent transmission and scattering of incident light
- Metamaterials integrated with optical slab concentrator could enable mm-scale photon management techniques to be exploited in high-efficiency multijunction solar cell concept

Future Plans (FY 2011 and beyond)

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- Project plans for FY2010 and FY2011:
  - Fabrication and demonstration of ultrathin quantum-well solar cell device with optimized optical coupling to device waveguide modes
  - Continued engineering of quantum-confined structures for improved optical absorption
  - Nanowire growth and device development on low-cost substrates and with heterostructures for improved power conversion efficiency
- Upcoming key milestones:
  - 7/1/10, 1/31/11: fabrication and characterization of quantum-well solar cell device incorporating substrate removal process, antireflection coating, and nanostructured scattering elements
  - 7/1/10, 1/31/11: demonstration of improved power conversion efficiency in nanowire photovoltaic devices

Mandatory Summary Slide

- New solar cell concepts offering high power conversion efficiency over broad range of illumination conditions likely to be needed for applications such as concentrating photovoltaics
- Quantum-well solar cells and related concepts offer theoretically predicted efficiencies of ~45% to >60% over broad range of illumination conditions
  - Plasmonics and nanoparticle scattering effects can facilitate simultaneously high efficiency in both optical absorption and photogenerated carrier collection
  - Nanowires offer alternate geometry for these concepts as well as potential for direct integration on low-cost substrates
- Key basic elements have been successfully demonstrated:
  - Photocurrent response over extended wavelength range due to quantum-well absorption
  - Plasmonic and nanoparticle scattering for improved long-wavelength optical absorption
  - Engineering of internal quantum well structure (potential steps within quantum well, dot-in-well structures) used to further improve optical absorption
  - Numerical simulations and designs developed for ultrathin, high-efficiency devices
  - III-V nanowire growth on Si substrates and photovoltaic device operation achieved
  - Nanowire core-shell heterostructure growth and growth on low-cost metal foil substrates achieved
- Program on track for demonstration of high-efficiency devices based on these concepts
- Potential for program expansion to exploit photon management concepts in more complex high-efficiency device geometries